Development of a facility for direct force measurements of LISA Gravitational Reference Sensor related disturbances

L.Carbone, A.Cavalleri, G.Ciani, R.Dolesi, M.Hueller, D.Tombolato, S.Vitale and W.J.Weber

Dipartimento di Fisica, Università di Trento, and I.N.F.N., Gruppo di Trento, 38050 Povo (TN), Italy

Email: carbone@science.unitn.it ciani@science.unitn.it

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• In the Drag-Free Control loop the spacecraft shields the test mass from external disturbances and follows it in its geodesic motion according to a position sensor

• The goal is to minimize the Test Mass residual acceleration with respect to the inertial frame

• The LISA position sensor has to be designed such that the residual acceleration is

$$a_n = \frac{f_{str}}{m} + \omega_p^2\left(x_n + \frac{F_{sat}}{M\,\omega_{DF}^2}\right) < 3\cdot 10^{-15}\ \frac{\mathrm{m}}{\mathrm{s}^2\sqrt{\mathrm{Hz}}}$$

Low parasitic forces f_{str}
Low residual couplings ω_p^2
High displacement sensitivity

LTP SENSOR DESIGN and FEATURES

• designed to meet LISA specifications in terms of both position and acceleration noise

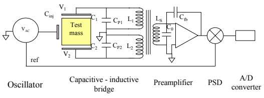
• The LTP sensor is a capacitive transducer, 100kHz resonant bridge readout

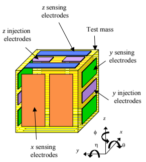
• electrode geometry is tuned to reduce electrostatic coupling without sacrifying sensitivity

• large gaps (up to 4 mm) to reduce several noise sources

• Mo/Sapphire composite structure, (matched) high thermal conductivity

• test mass: 46 mm cube (≈2 kg), Au-Pt alloy



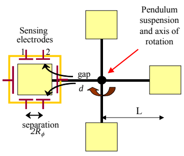


Validation of the noise model needs accurate ground testing

NOISE MODEL VERIFICATION: Verification of physical mechanism models and parameters measurement

Key instrument are torsion pendulum benches: torsion pendulums with hollow replicas of the TM inside a GRS prototype

A Multiple mass torsion pendulum to measure translational forces



ADVANTAGES

• Is directly sensitive to FORCES (instead of torques): fully "representative" of LISA
• Has Full sensitivity to any disturbance source arising inside the sensor (independently from the location)
• Sets model-independent force noise upper-limits
• Has high force sensitivity due to long arms
• Allows direct measurement of GRS relevant parameters:
  • sensor translational stiffness
  • dc bias term combinations giving pure force
  • temperature gradient effects
  • cross-coupling into x DOF
  • ...

Theoretical Thermal Noise Limit

• Resonant frequency:

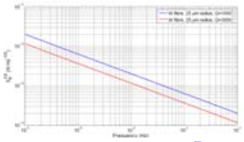
$$f_0 = \frac{1}{2\pi}\sqrt{\frac{\Gamma}{I}} \approx 0.8\,\mathrm{mHz}$$

• 1m long, 50 μm W fiber with Q ~ 1000, $\Gamma \approx 8\cdot10^{-8}$ Nm/rad
• 4 × 80g TM + 10 cm arm length
• ~ 400 g pendulum, $I \approx 3\cdot10^{-3}$ kg m²

• Thermal force noise limit (@1mHz):

$$S_F^{1/2} \approx \frac{S_N^{1/2}}{L} \approx \frac{1}{L}\sqrt{4k_BT\frac{\Gamma}{\omega Q}} \approx 180\,\mathrm{fN/Hz^{1/2}}$$

LISA Spec: 6 fN/Hz$^{1/2}$
LTP Spec: 60 fN/Hz$^{1/2}$



3 hour (10^4 sec) force resolution → $\Delta F \approx \frac{\sqrt{2}S_F^{1/2}}{\sqrt{T}} \approx 2$ fN

DRAWBACKS

• Prone to gravity gradients: $\propto L^4/r^5$

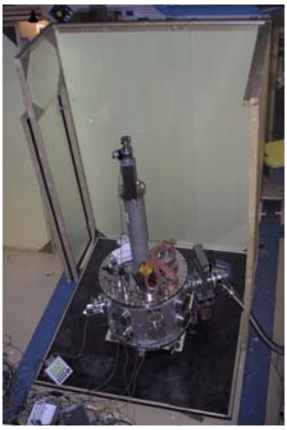
Increasing force sensitivity enhances coupling to gravity gradient noise

need to minimze pendulum gravitational quadrupole moment

• Need to minimize floor seismic motion

• Need to compensate sensor translational stiffness

THE TORSION PENDULUM FACILITY



• 4 degree of freedom manual micromanipulator (~ μm/ μrad resolution, for sensor alignment)
• 2 motorized linear stages (sub-μm resolution, for sensor alignment and automatized stiffness measurements)
• 2 degree of freedom manual micromanipulator (for pendulum rotational/vertical alignment)

• Independent Optical Readout: Autocollimator
• Tilt motion magnetic eddy current damper (τ ~ 200 sec)

• Optimized design for easy and fast assemblying
• CF160 flanges and windows for easy inspection and mantainance purposes

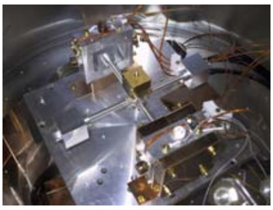
• 12 Pt100 thermometers (2mK/√Hz) (up to 24 sensors, internal and/or external)
• 3-axis Magnetometer (≈10^{-9}T/√Hz)
• External B field coils (up to 1G)
• 2-axis tiltmeter (100 nrad /√Hz)

• 250 liters vacuum vessel: (80cm wide, 60 high + 90 cm column)
• Turbomolecular pump 400 l/s (down to 10^{-7} mbar)

• Thermally controlled room inside class 10000 clean room
• Mu-Metal Shield (B field attenuation ≈10)

FIRST RUN: 4-MASS "DUMMY" PENDULUM

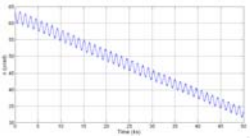
Performed with the aim of:
1. Commissioning and debug of the facility
2. Test of fiber performances
3. Investigation of pendulum complex dynamics

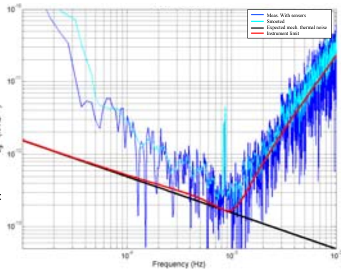


• 4 cubic Al masses, 3 cm side (same weight as the final 46mm hollow masses)
• cross shaped support, with 89 mm armlength
• Au-coated mirror for (commercial) optical readout
• $I \approx 2.6\cdot10^{-3}$ kg m²
• 50 μm W fiber, $\Gamma \approx 8\cdot10^{-8}$ Nm/rad, Q ≈ 1000
• 0.8 mHz twist resonant frequency

• 2 single axis capacitive sensors with very large gaps (6-8 mm, to suppress stray electrostatic effects)
• homebrew sensing circuitry (200 nrad Hz$^{-1/2}$)
• homebrew electrostatic actuation for PID twist control

A typical time series:

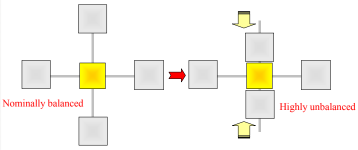




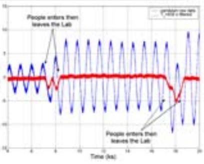
• approaching mechanical thermal noise around 1 mHz (roughly a factor 2 excess)
• limited by angular read-out noise above 1mHz
• likely limited by temperature fluctuations (excess noise still being investigated)

INVESTIGATION OF GRAVITY GRADIENT NOISE:

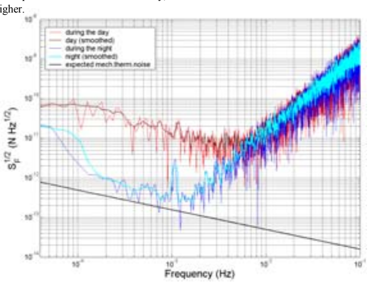
Purposely enhance pendulum quadrupole moment to amplify sensitivity to gravity gradients



This pendulum configuration is very sensitive to human activity.
The excess force noise observed in presence of human activity allows to estimate the environmental gravity gradient noise of the experimental site.



When human activity near the lab is reduced (night and week-ends) we do not observe any excess noise compared to the typical performances of the pendulum. With human activity, observed force noise is about a factor 50 higher.



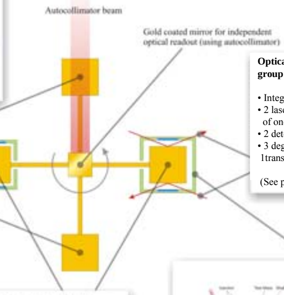
With tolerances of the assembly of order 100μm (or better), mass quadrupole moment of the final pendulum will be reduced at least by a factor 300. This makes gravity gradient noise to be negligible on the pendulum performances.

DIRECT FORCE CHARACTERIZATION OF THE LTP GRS:

(…going to be integrated soon…)

Four Test masses torsion pendulum

• Cross shaped support, 100 armlength
• Full Au-coated Al structure
• Full size (46mm) cubic hollow test masses
• Cubic Au-coated mirror for commercial optical optical readout



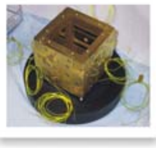
Optical Readout (ORO) developed by INFN group of Napoli

• Integrated on the stiffness compensator
• 2 laser beams shining on opposite faces of one test mass
• 2 detecting quadrant photodiodes
• 3 degree of freedom (2 rotational, 1translational) optical readout

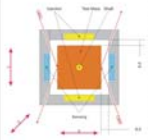
(See poster by L.Di Fiore et al)

LTP GRS Engineering Model

• Representative flight-hardware EM (See poster by Dolesi et al for details)



Electrically insulated test masses
For capacitive sensing and actuation



Stiffness Compensator and additional read-out
• 2 translational degree of freedom capacitive readout
• GRS EM comparable read-out performances
• Electrostatic stiffness equal to the one of GRS EM, to suppress tilt-twist coupling
• Very large gaps (6-8mm) to suppress stray electrostatic disturbances

This facility will allow to test the GRS engineering model with full-size test masses in flight representative conditions. It will allow to detect directly forces instead of torques and so it will make possible to observe and characterize any noisy force arising inside the GRS, independently from the location of the source. Upper limits on the overall force noise disturbance arising inside the GRS will be more stringent and independent from the model used to describe the single sources. Furthermore, the role of the noisy sources, producing force noise on the LISA test masses, will be easier to evaluate and model for LISA, leading to a more accurate verification of the noise model.